Detonation Limits in Rough Walled Tubes

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1 Introduction

The fact that almost all Chapman-Jouget detonation waves are unstable with a cellular structure suggests that instability plays an essential role in the self sustained propagation of the detonation wave. It is also found that the onset of detonation is associated with the development of the cellular structure [1]. It was also shown that when the cellular structure is destroyed by damping out the transverse waves, the detonation dies [2]. Lee postulated that the transverse pressure waves generated by the obstacles provide a strong mechanism of vorticity production through wave interactions, shock-vortex and shock-density interface interactions. Thus turbulence provides the mechanism for auto-ignition rapid combustion by turbulent mixing. He also demonstrated that when the transverse waves are damped out by acoustic absorbing walls, the combustion wave cannot maintain its high propagation velocity [3].

In rough walled tubes, the transition from deflagration to detonation is observed to be greatly facilitated. It appears the transverse waves generated by the rough walls facilitate the formation of the detonation [4]. Thus it seems logical to assume that rough wall tubes can also facilitate the propagation of detonation waves. This is in contrast to the general notion advanced by Zeldovichs theory of detonation limits that friction losses lead to the failure of the detonation [5]. Friction leads to velocity deficit which eventually leads to failure of the detonation when the velocity deficit is excessive. Since the generation of transverse waves facilitates the propagation of the detonation wave it is reasonable to assume that the detonation limits would be wider in a rough walled tube than in a smooth walled tube. The influence of wall roughness on detonation limits has not been investigated and it appears worthwhile to explore if wall roughness can widen the detonation limits. The present paper reports the results of an experimental investigation of detonation limits in rough wall tubes.

A Shchelkin spiral appears to be the simplest way to generate controlled wall roughness over a long distance of the propagation of the detonation wave. It is also of interest to investigate two types of detonable mixtures, one that is generally considered as a stable mixture with a regular cell pattern and an unstable mixture with a highly irregular cell pattern. The difference between the two mixtures lies in the temperature sensitivity of the reaction rate. Thus an unstable mixture would be where the reaction rate is highly sensitive to small temperature fluctuations.

The study of detonation in rough tubes was first carried out by Laffitte [6] and later Shchelkin [4] and Wheeler [7]. Gunoche carried out a systematic study and measured the steady state velocity of

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detonations in rough tubes. Of particular interest that steady state velocity as low as 30-40% of the CJ velocity of the mixture has been observed [8]. At such low velocities, shock ignition according to the classical ZND model of the detonation structure is no longer possible. DDT in rough tubes has also been widely studied but more relevant previous studies are those of Lee and co-workers where the limit of detonation regimes in rough walled (or obstacle filled) tubes are determined [9]. Also, of interest is the study by Manson et al. [10] where streak Schlieren photographs of detonation in rough tubes were taken illustrating the effect of the artificially induced transverse waves by the wall roughness on the intrinsic transverse instability of the cellular detonations.

2 Experimental Details

The detonation tube used in the present experiment consists of a steel driver section of 60 mm diameter and 1 m long. The polycarbonate test section of length 1.5 m is connected to the steel driver section. It is found that the detonation adjusts rapidly in the rough section and hence it is not necessary to use a long test section. Two tube diameters (12.7 mm and 50.8 mm) are used and for the wall roughness, a Shchelkin spiral of wire diameters (1.6 mm and 6.4 mm) and a pitch of one tube diameter is used. The wire diameters are chosen to give the same blockage ratio ($BR = 1 - (\frac{d}{D})^2$) of 0.44 in both tubes.

Ignition of the mixture is via a high energy spark from a high voltage, low inductance capacitor discharge. To ensure that a detonation is formed directly, a small volume of a more sensitive mixture (C_2H_2 + O_2) is bled into the ignition end of the driver section just prior to the experiment. Two mixtures, representative of the so called stable mixture with highly regular cell pattern and "unstable" mixture with highly irregular cell pattern were used. For the stable mixture C_2H_2 + $2.5O_2$ + 70%Ar is used and CH_4 + $2O_2$ is used to represent an unstable mixture.

For diagnostics, the detonation velocity is measured with periodically spaced optical fibers terminating in a photodiode. A schematic of the experimental set-up is shown in Fig. 1.

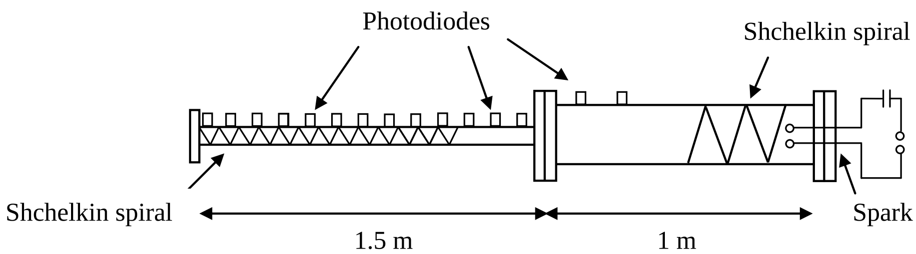

Figure 1: Schematic of Experimental Set-Up

3 Results and Discussions

For a given tube diameter, obstacle configuration (e.g. Shchelkin spiral), sensitivity of the mixture (e.g. composition, initial pressure) and explosive mixture, the detonation limit is obtained by progressively decreasing the initial pressure. Typical results of the detonation trajectories in the 12.7 mm diameter tube for C_2H_2 + $2.5O_2$ + 70%Ar are shown in Fig. 2 and for CH_4 + $2O_2$ in Fig. 3. Similar results are seen in the 50.8 mm tube for both mixtures. Prior to entering the rough section of the tube, there is a short section of 0.4 m of smooth tube where the detonation can be used to serve as a reference. In this section, the velocity is generally found to correspond closely to theoretical CJ value (with a typical velocity deficit of 7%). When the detonation enters the rough section, the velocity adjusts rapidly to a lower value. After this adjustment, the detonation propagates at a more or less constant velocity in the rough section, despite being constantly perturbed by the spiral. As the pressure is lowered towards the limit, the velocity in the rough section decreases. As the pressure is lowered to a certain critical value, luminosity significantly decreases and photodiodes do not always pick up signal of detonation wave. Here, there are a lot of fluctuations due to the sensitivity at this critical pressure. At a pressure lower than this critical value we do not get any signal. We say that the detonation fails at this critical pressure and thus we defined the limiting pressure of this mixture in the rough tube. It is interesting to note that two things can happen at the limit; no combustion wave occurs in the rough section and the combustion quenches or we get a slow flame and the photodiodes just don't pick it up.

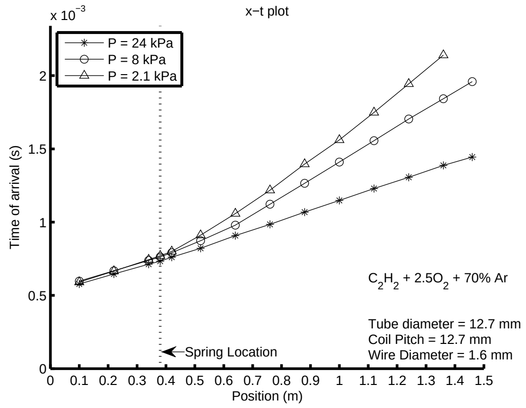

Figure 2: Results for C_2H_2 + $2.5O_2$ + 70%Ar in the 12.7 mm tube

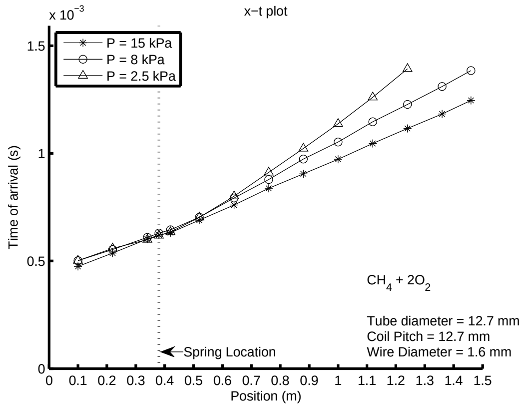

Figure 3: Results for CH_4 + $2O_2$ in the 12.7 mm tube

The velocity variation with pressure for C_2H_2 + $2.5O_2$ + 70%Ar in the 12.7 and 50.8 mm diameter tubes are shown in Fig. 4. There are numerous important observations. The velocity in the bigger tube is higher than in the smaller tube. There is an abrupt drop in velocity at some critical pressure. After this drop, we continue to get low velocity at about 50% V_{CJ}. Both tube diameters have about the same velocity value before and after the drop. Velocity continues to decrease with decreasing pressure until some critical value when nothing is observed.

Also shown are the results for the smooth tube with both diameters [11]. The velocity in the smooth tube is $0.8V_{CJ} \leq V \leq V_{CJ}$, unlike the rough tube. An abrupt drop in velocity signals detonation limit, however limiting pressure in the smooth tube is higher than that in the rough tube. In the 12.7 mm tube, the smooth limit is 3 kPa [11] and the rough limit is 2 kPa. In the 50.8 mm tube, the smooth limit is 1 kPa [11] and the rough limit is 0.5 kPa.

An important conclusion is that the rough tube, despite making the detonation slower, can maintain continued propagation when compared to a smooth tube. So the roughness promotes turbulence and slower velocity but seems to air detonation propagation. It is also interesting to note that the abrupt drop in velocity observed in this mixture occurs at d/λ =1, within estimation errors of λ.

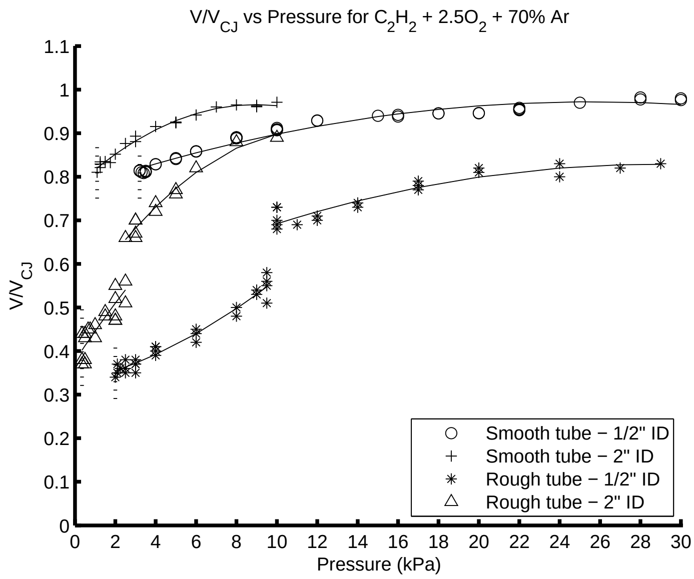

Figure 4: V/V_{CJ} vs. Pressure for C_2H_2 + $2.5O_2$ + 70%Ar in the 12.7 and 50.8 mm tubes

The velocity variation with pressure for CH4 + 202 in the 12.7 and 50.8 mm diameter tubes are shown in Fig. 5 and Fig. 6, respectively.

Similar to the stable mixture, the velocity in the smooth tube is higher than in the rough tube. However, this abrupt velocity drop is not observed in either tube. Again, the limiting pressure is extended in the rough tube. In the 12.7 mm tube, the smooth limit is 14 kPa [11] and the rough limit is 2 kPa. In the 50.8 mm tube, the smooth limit is 4 kPa [11] and the rough limit is 0.5 kPa.

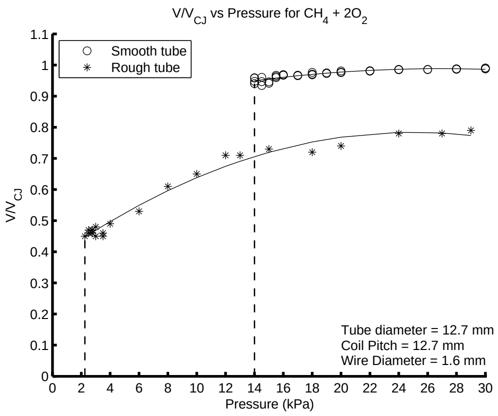

Figure 5: V/V_{CJ} vs. Pressure for CH_4 + $2O_2$ in the 12.7 mm tube

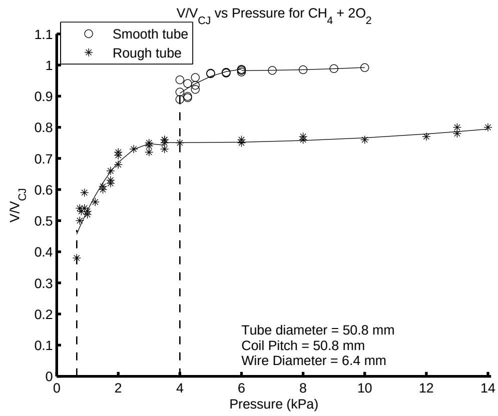

Figure 6: V/V_{CJ} vs. Pressure for CH_4 + $2O_2$ in the 50.8 mm tube

4 Concluding Remarks

The present study indicates that wall roughness extends the range of detonability limits i.e. steady self-sustained propagation can be obtained over a wider range of initial pressures. Thus confirms that wall roughness facilitates the propagation of detonation by the generation of turbulence and transverse waves. A wider range of propagation is observed in spite of a larger velocity deficit due to the wall roughness.

Thus this indicates that classical theory of Zeldovich where frictional losses are considered as being responsible for the failure of the detonation [5] does not appear to be the case. The results support the notion that the generation of turbulence and transverse waves actually facilitate the self-sustained propagation of detonation waves. Thus it serves as an indirect indication that instability and transverse waves are essential to the propagation of detonation. In rough tubes, it appears that the generation of turbulence and transverse waves are controlled by the wall roughness which renders stability properties of the mixture less important. Thus the results for stable and unstable mixtures showed less of a difference for a given tube diameter and obstacle configuration.

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